

Chapter 18

Tailored Responses to Simultaneous Drought Stress and Pathogen Infection in Plants

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18.1 Introduction

With the changing global climate, a series of environmental factors are modified concurrently, along with changes in their intensity and timing. Thus plants are exposed to combinations of abiotic and biotic stressors whose combined impact can adversely affect crop performance and survival (Mittler 2006; Atkinson and Urwin 2012). Of the possible biotic and abiotic stress combinations, simultaneous drought stress and pathogen infection is one of the best studied combinations (Mayek-Perez et al. 2002; McElrone et al. 2003; Sharma et al. 2007; Király et al. 2008; Xu et al. 2008; Carter et al. 2009; Wang et al. 2009; Ramegowda et al. 2013). Drought is one of the most damaging and frequently occurring abiotic factors that can potentially alter the outcome of plant–pathogen interactions (Sharma and Pande 2013). Phenotypic responses of plants exposed to drought stress and pathogen infection vary depending on the severity and duration of each stress and also differs with pathogen type, e.g., fungi, oomycetes, bacteria, or viruses (Olson et al. 1990; McElrone and Forseth 2004; Achuo et al. 2006; Xu et al. 2008). Based on these factors, the combination of drought and pathogen infection can have two outcomes. In the first scenario, the two stressors can act additively, and result in enhanced damage to the plant. For example, drought has been shown to aggravate many fungal (Mayek-Perez et al. 2002), bacterial (McElrone et al. 2001; Mohr and Cahill 2003), and viral (Olson et al. 1990; Prasch and Sonnewald 2013) infections in plants. The susceptibility is attributed to drought-induced increase in abscisic acid (ABA) in plants which then suppresses their defense against pathogens mediated by salicylic acid, jasmonic acid, and ethylene signaling. Few other drought-induced physiological changes like accumulation of osmolytes and nutrient leakage have been reported

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to enhance disease in plants by enriching nutrient supply for the pathogens (Mayek-Perez et al. 2002). Additionally, some pathogens can influence plant water relations leading to low water potential in plant cells, thereby, increasing the effects of water deficit (English-Loeb et al. 1997; Smit and Vamerali 1998; Audebert et al. 2000; Amtmann et al. 2008; Goel et al. 2008; Mittler and Blumwald 2010; Choi et al. 2013). In the second scenario, the simultaneous exposure to drought and pathogen infection can alleviate the effect of either or both the stresses thereby enhancing plants tolerance to the stresses. For example, drought stress has been shown to increase plant tolerance towards some pathogens like *Botrytis cinerea* and *Pseudomonas syringae* (Achuo et al. 2006; Ramegowda et al. 2013). Moreover, pathogen-mediated alleviation of drought stress has also been reported in some cases. For example, infection with *Cucumber mosaic virus* (CMV) led to improved drought tolerance of plants like *Capsicum annum*, *Solanum lycopersicum* and *Nicotiana tabacum* (Xu et al. 2008). This has been attributed to increased levels of osmoprotectants (trehalose) and antioxidants (anthocyanins and ascorbic acid) (Xu et al. 2008). Infection with *Tobacco mosaic virus* (TMV) enhanced ABA level in *N. tabacum* (Whenham et al. 1986), which points towards the probable role of ABA in virus infection-mediated drought resistance in plants. Thus, ABA might act as a global regulator of stress responses and facilitate fine-tuning of plant stress responses to focus on the more severe threat (Anderson et al. 2004; Yasuda et al. 2008; Ton et al. 2009).

18.2 Plant Responses Under Combined Stress: Tailored Responses

Plants have developed specific mechanisms that allow them to detect environmental changes and respond to complex stress conditions. Findings from the recent studies suggest that some of the responses triggered under combined stress are different from the responses seen in plants exposed to the same stressors individually (Rizhsky et al. 2002, 2004; Anderson et al. 2004; Mittler 2006; Asselbergh et al. 2008; Atkinson and Urwin 2012). Combinatorial stress results in novel interactions between signaling components, which makes the response of the plant distinct from its response to single stresses. Thus, under combined stress, plants exhibit “tailored adaptation strategies,” which are customized specifically to the stress combinations (Atkinson and Urwin 2012). Rather than producing an additive response pertaining to each stress, plants instigate some entirely new responses specific for each stress combination (Atkinson and Urwin 2012; Atkinson et al. 2013; Prasch and Sonnewald 2013, 2015; Rasmussen et al. 2013; Rivero et al. 2013; Bostock et al. 2014; Kissoudis et al. 2014; Suzuki et al. 2014). This differential response is necessary to efficiently balance resource allocation between growth and defense and to help the plant respond to stress in a way that does not hamper its fitness (Herms and Mattson 1992; Smith 2007; Bechtold et al. 2010).

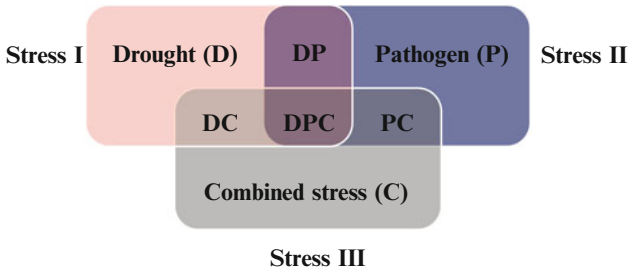
Plant's response to concurrently occurring biotic and abiotic stresses varies with the severity, timing, and duration of each of the stressors involved (Atkinson and Urwin 2012). The detailed study of plant responses to combined drought and pathogen infection has revealed that some of the responses shown were similar to that evoked under the individual stresses (Fig. 19.1a). Such responses are thus "shared" between a plant subjected to the two stressors separately and in combination. Apart from the shared responses, several unique responses (indicated in the Fig. 19.1a as "C") are also seen under combined stress, implying that the response is not merely the additive effect of single stress responses (Atkinson and Urwin 2012; Atkinson et al. 2013). In certain situations, plant prioritizes its response towards the more severe threat, i.e., the stress which is more damaging and requires immediate attention.

Thus, the adaptation strategies of plants under combined stress constitute different types of responses depending upon the nature and severity of the stresses (Fig. 19.1b). As mentioned above, the response can be new and not observed under either of the individual stress conditions (unique response) or be similar to the responses evoked by each of the single stresses (shared responses). However, these shared responses can be selectively activated or repressed under combined stress and thus be tailored according to the varying severity of the two stresses encountered (prioritized responses). In some cases, the stress combination can also lead to nullification of the effects of the two stresses on plants (canceled response). Therefore, in order to truly characterize the response of plants to simultaneously occurring stresses, each stress combination should be studied as an entirely new stress (Mittler and Blumwald 2010). A brief discussion on the different categories of tailored response is provided in the section below.

18.2.1 Unique Responses

Recent studies have indicated that the combination of drought and pathogen evokes unique responses in plants, which are not seen when each stress is imposed individually (Choi et al. 2013; Prasch and Sonnewald 2013). These unique responses have been studied only at the molecular level. For example, the exposure of *Vitis vinifera* plants to the combined drought and *Xylella fastidiosa* infection for 4 weeks led to the modulation of 90 transcripts out of which 39 were unique to the combined stress treatment (Choi et al. 2013). Similar results were reported in yet another study wherein the combined virus, drought, and heat treatment to *A. thaliana* plants led to differential expression of 776 unique transcripts (Prasch and Sonnewald 2013; Ramegowda and Senthil-Kumar 2015). These "unique" genes were not seen in transcriptional profile of the individually stressed plants. Re-analysis of the microarray results of Prasch and Sonnewald (2013) by Ramegowda and Senthil-Kumar (2015) revealed that these unique genes constitute several WRKY transcription factors, signaling proteins like receptor like kinases and protein phosphatases. These results suggest that combined stress treatment leads to a reprogramming of gene expression

a



b

	Control	Drought	Pathogen	Combined drought and pathogen stress	
1.	N	A	B	C	← Novel responses
2.	N	A	B	A	} Prioritized
3.	N	A	B	B	
4.	N	A	B	A ⁻ B ⁻	← Cancelled

c

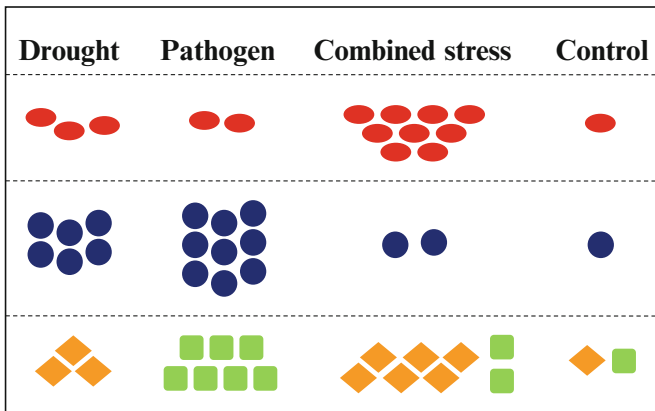


Fig. 19.1 Hypothetical model depicting tailored responses in plants exposed to combined drought stress and pathogen infection. (a) Venn diagram shows plant’s response to drought (stress I), pathogen (stress II), and their combination (stress III, an altogether new stress). DC—responses shared between drought stress and combination stress, PC—responses shared between pathogen and combined stress, and DPC—responses shared among drought stress, pathogen and combined drought and pathogen. (b) Schematic representation of modulation of plant adaptation strategies under combined stress. N—response under optimal growth conditions, A—response to drought, B—response to pathogen infection, last column illustrates the three types of tailored responses under combined stress. Row 1—novel responses (c) induced only under combined stress. These responses are not seen under single stress situations. Row 2 and 3—under combined stress, the adaptation

of plants. The presence of combined stress specific unique molecular responses have also been seen in case of drought and heat stress combinations (Rizhsky et al. 2002, 2004; Rampino et al. 2012; Johnson et al. 2014) which further authenticates the tailoring of molecular responses to stress combinations. Although not much information is available in this regards, this preliminary information supported by further studies is useful to unravel the mechanism behind the unique responses seen under the combined stress conditions.

18.2.2 *Prioritized Responses*

Apart from the unique responses, certain responses, characteristic of the individual stresses, are also observed when plants are exposed to combined stresses. Being common to the two individual stress conditions, these responses are termed as shared responses. However, these shared responses are further attuned to the combined stress. Plants when challenged with two stresses simultaneously prioritize their response towards the more damaging stress, overriding the defense pathway for the less severe stress (Prasch and Sonnewald 2013; Rasmussen et al. 2013). This results in suppression of responses to the stress, which is less severe. For example, plants exposed to water deficit and pathogen infection simultaneously often show weakened defenses and enhanced susceptibility to the pathogen (Audebert et al. 2000; Amtmann et al. 2008; Goel et al. 2008; Mittler and Blumwald 2010). In the study conducted by Atkinson and Urwin (2012), the combined effect of drought and infection with root-knot nematodes *Meloidogyne incognita* on nutritional quality of tomato was investigated. The physiological responses of the plants were compared for different stress treatments and the levels of antioxidants in fruits were analyzed. Significantly higher levels of flavonoids were found in infected plants compared to controls, while a little or no change in flavonoid concentration was reported as a result of water stress only. Interestingly, when the two stresses were applied simultaneously, the heightened accumulation of flavonoids seen under nematode stress was reduced to a level which was not significantly different from the control and water-stressed plants. This can be explained by the drought-induced accumulation of ABA which in turn inhibits the transcription of defense and pathogen-responsive genes, thus preventing nematode-induced flavonoid accumulation (Anderson et al. 2004). The carotenoids (lycopene and β -carotene) concentration was significantly

Fig. 19.1 (continued) strategies are prioritized for the more severe stress among the two. In 2 and 3, response under combined stress resembles the response to drought and pathogen alone, respectively. Row 4—Responses evoked independently under single stresses are absent under combined stress. Fig. 19.1 (continued) (c) Illustration depicting tailored molecular responses under combined stress. Each symbol represents a gene product and the number represents their level relative to control. In row 1 and 2, level of the gene product shared between two stresses changes in magnitude under combined stress. Row 3 depicts response at the gene level prioritized for a particular stress, in this case drought. The proposed models are general and can be extended to few other stress combinations as well

reduced in water-stressed tomatoes but remained unaffected by nematode stress. However, under combined stress the expected reduction in the carotenoids level was not seen. The antagonism between drought-induced ABA and ethylene may be the reason for observed inhibition in carotenoid accumulation (Anderson et al. 2004). Additionally, when water deficit and nematode infection occurred in combination, the plant's physiological response was more similar to that of water stress alone in the early harvested tomatoes but to nematode stress alone in the late-harvested tomatoes. These results support the hypothesis that plant stress responses are specifically tailored to the exact combination of environmental stresses encountered, to the extent that the plant responds to whichever stress is most severe, overriding the pathway for the less severe stress (Anderson et al. 2004). The prioritization of responses as a mechanism to focus plants metabolism in deploying their adaptation strategies towards the high impacting stress can be seen as an effective strategy supporting the concept of growth-defense trade-offs in plants (Huot et al. 2014).

18.2.3 Canceled Responses

Interaction of two stresses can also lead to amplification of the tolerance responses, i.e., when two stresses are imposed simultaneously, their effect on plants get “canceled” resulting in enhanced plant tolerance to combined stress as compared to individual stress conditions (Rasmussen et al. 2013). Adaptation strategies that are not sufficient to protect the plants under individual stresses act in unison under the combined stress and the negative impact of the two stresses is canceled. Canceled responses were reported under salt and heat stress combination. For example, some proteins, induced during salt stress (e.g., choline monooxygenase, chloroplastic ATP synthase, V-type proton ATPase catalytic subunit A) and heat stress (e.g., heat shock 70 kDa protein) in *Suaeda salsa*, were unchanged during combined salt and heat treatment (Li et al. 2011). Canceled response in case of drought and pathogen stresses have not yet been reported.

In addition to the above mentioned types of responses that are exhibited by plants as a part of tailored adaptation strategy to counter the combined stress, the “tailoring” can also be observed at the molecular level. Combined stress may lead to the expression of a new set of genes, which are not expressed under individual stress conditions. The molecular response of plants to the two stress conditions and their combination also consists of several commonly regulated genes. However, a change in their expression level can be seen under combined stress (Prasch and Sonnewald 2013). Broadly there can be three different scenarios as indicated in Fig. 19.1c. In case I, the gene product reached beyond the additive level under combined stress, while in case II, the relative level declined and reached closer to that seen under control. Case III depicts prioritization of responses towards a particular stress, wherein the gene product related to plant response to one stress (in this case, drought) is upregulated at the cost of the gene product involved in defense against the other (pathogen stress) (Fig. 19.1c).

18.3 Tailored Responses of Plants to Combined Drought and Pathogen Stress

18.3.1 Morphophysiological Responses

A study comparing the responses of ten ecotypes of *Arabidopsis thaliana* under two individual and combined abiotic stresses revealed that there were no unique morphophysiological responses evoked under combined stress. The responses observed under combined stress were shared and majorly prioritized for one of the stresses (Vile et al. 2012). Some recent reports have indicated the prioritization of stomatal defense responses under simultaneously imposed biotic and abiotic stimuli. When *Vicia faba* and *A. thaliana* were subjected to a combination of biotic stress (*Escherichia coli* or *Pseudomonas syringae*) and several abiotic stresses including water deficit, stomatal responses to abiotic stresses were found to override the responses to biotic stresses (Ou et al. 2014). Similar inferences were obtained from another study on the effect of combined drought and virus infection on *A. thaliana* plants. The microscopic analysis of length-width ratio of stomata of *A. thaliana* plants subjected to concurrent *Turnip mosaic virus* (TuMV) infection, heat, and drought stress in single, double, and triple combinations revealed that stomata were closed under combined treatments of virus and drought, and virus and heat, as well as during the triple stress, while heat stress alone or virus infection resulted in stomatal opening (Prasch and Sonnewald 2013). Also, *X. fastidiosa*, a wilt causing pathogen, influenced the water status (indicated by measurement of leaf water potential, stomatal conductance and transpiration rate) of *V. vinifera* and thus aggravated the effect of drought on the plants (Choi et al. 2013).

18.3.2 Transcriptomic and Metabolic Responses

Till date only four studies have documented the global transcriptome and metabolome changes in plants simultaneously exposed to combinations of various biotic and abiotic stresses (Atkinson et al. 2013; Choi et al. 2013; Prasch and Sonnewald 2013; Rasmussen et al. 2013). The recurrent observation from all these studies is that the adaptation strategies of a plant are specifically tailored in accordance with the combination of stresses it encounters and their severity. As mentioned earlier, the molecular responses can be either unique or shared. A study undertaken by Rasmussen et al. (2013) revealed that 61 % of the transcriptome changes in *A. thaliana* in response to combined stress were not predictable from the responses to single stress treatments (cold, heat, high light, salt, and flagellin). The uniqueness in molecular response seen under combined stress stems from the induction of certain unique transcripts and from selective activation or repression of transcripts responsive to a particular stress. A total of 23 genes were specifically expressed when *A. thaliana* plants were subjected to a combination of drought, heat, and TuMV

(Prasch and Sonnewald 2013). Among these most of the genes encoded stress responsive proteins. Ramegowda and Senthil-Kumar (2015) reanalyzed the transcriptomic data from the above experiment using Bio Conductor package in R statistical program and reported a total of 1370 genes differentially expressed under combined drought and virus infection. Interestingly, out of 1370 genes, 98 genes were unique to virus stress and 157 were unique to drought stress, while 776 were unique to combined drought stress and virus infection. The stress-specific genes upregulated under individual drought and virus infection were 16 and 29, respectively, and the number increased to 72 under combined stress (Prasch and Sonnewald 2013; Pandey et al. 2015). Most of the stress combination specific genes belonged to the category of transcription factors and other regulatory genes including dehydration responsive element binding 2A (DREB2A) and genes encoding zinc finger proteins. Other combined stress associated genes reported were those encoding pentatricopeptide repeat containing protein, abi5 binding protein (AFP1), cold-regulated 47, and universal stress protein family protein. A time-dependent modulation was shown in the transcriptome of *V. vinifera* plants upon exposure to combined drought and *X. fastidiosa* infection (Choi et al. 2013). No significant change in the transcriptome was seen in the early phase (4 weeks posttreatment); however, the number of differentially expressed genes increased with increasing stress exposure (8 weeks posttreatment) and a total of 90 unique transcripts were seen in combined stressed plants. An early upregulation of 9-cis epoxycarotenoid dioxygenase (NCED), an ABA biosynthesis gene, was also reported only under combined stress. These genes are characteristic examples of unique responses under combined stress.

Apart from unique responses, prioritized molecular responses have also been observed under combined stresses. Rasmussen et al. (2013) reported that among the transcripts resulting in antagonistic responses under combined stress, 5–10 % are prioritized under combined stress. In another report, the transcript profile of *A. thaliana*, under simultaneously imposed drought and *Heterodera schachtii*, was shown to be more similar to the expression profile of the plants exposed to water deficit alone than that of the nematode infected plant (Atkinson et al. 2013). Prasch and Sonnewald (2013) also provided evidence for the prioritization of plant's responses towards abiotic stress at the cost of defense responses against biotic stress. The enhanced expression of defense genes that mediates basal as well as *R*-gene-mediated resistance in virus infected *A. thaliana* was abolished under combined virus, heat, and drought stress. In the combined stress situation, only six *R* genes were differentially regulated and none of them were commonly regulated between virus and combined stress, indicating changes in the defense program. One of the genes exclusively downregulated under combined stress was ribosomal protein S6 (*RPS6*). *RPS6* has been shown to mediate resistance via enhanced disease susceptibility (*EDS1*) against *P. syringae* pv. *syringae* effector HopA1 (Kim et al. 2009) as well as against fungal pathogens. These observations indicate the differential response of plants towards abiotic and biotic stresses, which resulted in preferential deactivation of defense responses against various pathogens.

The cytoplasmic protein response (CPR) marker genes constitute another class of shared molecular response under combined drought and virus infection in *A. thaliana* (Prasch and Sonnewald 2013). It is speculated that enhanced CPR

supports viral-replication and systemic cell-to-cell spread of the virus in the plant, resulting in increased susceptibility of the host plants (Mayer and Bukau 2005; Prasch and Sonnewald 2013).

Metabolic profiling of plants subjected to combined drought and TuMV treatment revealed the preferential accumulation of tricarboxylic acid (TCA) cycle intermediates and the amino acids derived from them (Prasch and Sonnewald 2013). Under drought stress, increased levels of proline help to protect against osmotic stress (Hanson and Hitz 1982). Interestingly, a combination of drought and virus infection resulted in increased proline accumulation (Prasch and Sonnewald 2013). Altogether, the results obtained from transcriptomic and metabolic studies reflect upon the complexity in plant's responses under the combined stress scenario and highlight the fact that the mechanism of plants' tolerance to combined stresses cannot be completely understood from single stress studies.

18.4 Conclusions and Future Perspectives

The changing climatic conditions impact plants both in terms of stress severity and number of stresses. Hence, understanding the effect of the combined abiotic and biotic stresses on growth and development of plants is important. It has been shown in recent studies that plants tailor some of their responses to the stress combination. This either involves complete reprogramming of plant molecular responses leading to the prioritization of responses towards the more severe stress, or modulation in the magnitude of the shared responses. The tailored responses depends on the nature and intensity of the stresses involved, the age of the plant at which the stress is encountered, and the inherent stress tolerance nature of the plant species.

Recent studies have shed preliminary, but useful information on the combined stress response of plants. Further identification of the genes involved in tailored response and their complete mechanistic understanding can help in formulating the signaling networks and pathways involved in combined stress response. This can not only help in strengthening our knowledge about the unconventional and unique plant adaptation strategies but can also provide important leads for the development of crops that can efficiently tolerate simultaneously occurring drought and pathogen stresses.

Acknowledgements Projects at MS-K Lab are supported by National Institute of Plant Genome Research core funding and DBT-Ramalingaswami re-entry fellowship grant (BT/RLF/re-entry/23/2012). A.C. and P.P. acknowledge DBT-Junior Research Fellowship (JRF, DBT/2014/NIPGR/261) and DST-SERB young scientist grant (SB/YS/LS-71/2014), respectively, for the financial support. Authors thank Mrs. Urooj Fatima for critical reading of the manuscript.

References

- Achuo EA, Prinsen E, Höfte M. Influence of drought, salt stress and abscisic acid on the resistance of tomato to *Botrytis cinerea* and *Oidium neolycopersici*. *Plant Pathol.* 2006;55:178–86.
- Amtmann A, Troufflard S, Armengaud P. The effect of potassium nutrition on pest and disease resistance in plants. *Physiol Plant.* 2008;133:682–91.

- Anderson JP, Badruzaufari E, Schenk PM, Manners JM, Desmond OJ, Ehlert C. Antagonistic interaction between abscisic acid and jasmonate-ethylene signaling pathways modulates defense gene expression and disease resistance in *Arabidopsis*. *Plant Cell*. 2004;16:3460–79.
- Asselbergh B, De Vleeschauwer D, Höfte M. Global switches and fine-tuning-ABA modulates plant-pathogen defense. *Mol Plant Microbe Interact*. 2008;21:709–19.
- Atkinson NJ, Urwin PE. The interaction of plant biotic and abiotic stresses: from genes to the field. *J Exp Bot*. 2012;63:3523–43.
- Atkinson NJ, Lilley CJ, Urwin PE. Identification of genes involved in the response of *Arabidopsis* to simultaneous biotic and abiotic stresses. *Plant Physiol*. 2013;162:2028–41.
- Audebert A, Coyne D, Dingkuhn M, Plowright R. The influence of cyst nematodes (*Heterodera sacchari*) and drought on water relations and growth of upland rice in Côte d'Ivoire. *Plant Soil*. 2000;220(1–2):235–42.
- Bechtold U, Lawson T, Mejia-Carranza J, Meyer RC, Brown IR, Altmann T, Ton J, Mullineaux PM. Constitutive salicylic acid defences do not compromise seed yield, drought tolerance and water productivity in the *Arabidopsis* accession C24. *Plant Cell Environ*. 2010;33:1959–73.
- Bostock RM, Pye MF, Roubtsova TV. Predisposition in plant disease: exploiting the nexus in abiotic and biotic stress perception and response. *Annu Rev Phytopathol*. 2014;52:517–49.
- Carter AH, Chen XM, Garland-Campbell K, Kidwell KK. Identifying QTL for high-temperature adult-plant resistance to stripe rust (*Puccinia striiformis* f. *sp. tritici*) in the spring wheat (*Triticum aestivum* L.) cultivar 'Louise'. *Theor Appl Genet*. 2009;119:1119–28.
- Choi H-K, Iandolino A, da Silva FG, Cook DR. Water deficit modulates the response of *Vitis vinifera* to the Pierce's disease pathogen *Xylella fastidiosa*. *Mol Plant Microbe Interact*. 2013;26(6):643–57.
- English-Loeb G, Stout MJ, Duffey SS. Drought stress in tomatoes: changes in plant chemistry and potential nonlinear consequences for insect herbivores. *Oikos*. 1997;79:456–68.
- Goel AK, Lundberg D, Torres MA, Matthews R, Akimoto-Tomiya C, Farmer L, Dangl JL, Grant SR. The *Pseudomonas syringae* type III effector HopAM1 enhances virulence on water-stressed plants. *Mol Plant Microbe Interact*. 2008;21:361–70.
- Hanson AD, Hitz WD. Metabolic responses of mesophytes to plant water deficits. *Annu Rev Plant Physiol Plant Mol Biol*. 1982;33:163–203.
- Hermes DA, Mattson WJ. The dilemma of plants: to grow or defend. *Q Rev Biol*. 1992;67:283–335.
- Huot B, Yao J, Montgomery BL, He SY. Growth-defense tradeoffs in plants: a balancing act to optimize fitness. *Mol Plant*. 2014;7(8):1267–87.
- Johnson SM, Lim FL, Finkler A, Fromm H, Slabas AR, Knight MR. Transcriptomic analysis of *Sorghum bicolor* responding to combined heat and drought stress. *BMC Genomics*. 2014;15:456.
- Kim SH, Kwon SI, Saha D, Anyanwu NC, Gassmann W. Resistance to the *Pseudomonas syringae* effector HopA1 is governed by the TIR-NBSLRR protein RPS6 and is enhanced by mutations in SRFR1. *Plant Physiol*. 2009;150:1723–32.
- Király L, Hafez YM, Fodor J, Király Z. Suppression of *Tobacco mosaic virus*-induced hypersensitive-type necrotization in tobacco at high temperature is associated with downregulation of NADPH oxidase and superoxide and stimulation of dehydroascorbate reductase. *J Gen Virol*. 2008;89:799–808.
- Kissoudis C, van de Wiel C, Visser RGF, van der Linden G. Enhancing crop resilience to combined abiotic and biotic stress through the dissection of physiological and molecular crosstalk. *Front Plant Sci*. 2014;5:207.
- Li W, Zhang C, Lu Q, Wen X, Lu C. The combined effect of salt stress and heat shock on proteome profiling in *Suaeda salsa*. *J Plant Physiol*. 2011;168(15):1743–52.
- Mayek-Perez N, Garcia-Espinosa R, Lopez-Castaneda C, Acosta-Gallegos JA, Simpson J. Water relations, histopathology and growth of common bean (*Phaseolus vulgaris* L.) during pathogenesis of *Macrophomina phaseolina* under drought stress. *Physiol Mol Plant Pathol*. 2002;60:185–95.

- Mayer MP, Bukau B. Hsp70 chaperones: cellular functions and molecular mechanism. *Cell Mol Life Sci.* 2005;62:670–84.
- McElrone AJ, Forseth IN. Photosynthetic responses of a temperate liana to *Xylella fastidiosa* infection and water stress. *J Phytopathol.* 2004;152:9–20.
- McElrone AJ, Sherald JL, Forseth IN. Effects of water stress on symptomatology and growth of *Parthenocissus quinquefolia* infected by *Xylella fastidiosa*. *Plant Dis.* 2001;85:1160–4.
- McElrone AJ, Sherald JL, Forseth IN. Interactive effects of water stress and xylem-limited bacterial infection on the water relations of a host vine. *J Exp Bot.* 2003;54:419–30.
- Mittler R. Abiotic stress, the field environment and stress combination. *Trends Plant Sci.* 2006;11:15–9.
- Mittler R, Blumwald E. Genetic engineering for modern agriculture: challenges and perspectives. *Annu Rev Plant Biol.* 2010;61:443–62.
- Mohr PG, Cahill DM. Abscisic acid influences the susceptibility of *Arabidopsis thaliana* to *Pseudomonas syringae* pv. tomato and *Peronospora parasitica*. *Funct Plant Biol.* 2003;30:461–9.
- Olson AJ, Pataky JK, D'Arcy CJ, Ford RE. Effects of drought stress and infection by maize dwarf mosaic virus on sweet corn. *Plant Dis.* 1990;74:147–51.
- Ou X, Gan Y, Chen P, Qiu M, Jiang K, et al. Stomata prioritize their responses to multiple biotic and abiotic signal inputs. *PLoS One.* 2014;9(7), e101587.
- Pandey P, Ramegowda V, Senthil-Kumar M. Shared and unique responses of plants to multiple individual stresses and stress combinations: physiological and molecular mechanisms. *Front Plant Sci.* 2015;6:723.
- Prasch CM, Sonnewald U. Simultaneous application of heat, drought and virus to *Arabidopsis thaliana* plants reveals significant shifts in signaling networks. *Plant Physiol.* 2013;162(4):1849–66.
- Prasch CM, Sonnewald U. Signaling events in plants: stress factors in combination change the picture. *Environ Exp Bot.* 2015;114:4–14. doi:10.1016/j.envexpbot.2014.06.020.
- Ramegowda V, Senthil-Kumar M. The interactive effects of simultaneous biotic and abiotic stresses on plants: mechanistic understanding from drought and pathogen combination. *J Plant Physiol.* 2015;176:47–54.
- Ramegowda V, Senthil-Kumar M, Ishiga Y, Kaundal A, Udayakumar M, Mysore KS. Drought stress acclimation imparts tolerance to *Sclerotinia sclerotiorum* and *Pseudomonas syringae* in *Nicotiana benthamiana*. *Int J Mol Sci.* 2013;14(5):9497–513.
- Rampino P, Mita G, Fasano P, Maria G, Aprile A, Dalessandro G, De Bellis L, Perrotta C. Novel durum wheat genes up-regulated in response to a combination of heat and drought stress. *Plant Physiol Biochem.* 2012;56:72–8.
- Rasmussen S, Barah P, Suarez-Rodriguez MC, Bressendorff S, Friis P, Costantino P, Bones AM, Nielsen HB, Mundy J. Transcriptome responses to combinations of stresses in *Arabidopsis*. *Plant Physiol.* 2013;161:1783–94.
- Rivero RM, Mestre TC, Mittler R, Rubio F, Garcia-Sanchez F, Martinez V. The combined effect of salinity and heat reveals a specific physiological, biochemical and molecular response in tomato plants. *Plant Cell Environ.* 2013;37:1059–73.
- Rizhsky L, Liang HJ, Mittler R. The combined effect of drought stress and heat shock on gene expression in tobacco. *Plant Physiol.* 2002;130:1143–51.
- Rizhsky L, Liang H, Shuman J, Shulaev V, Davletova S, Mittler R. When defense pathways collide. The response of *Arabidopsis* to a combination of drought and heat stress. *Plant Physiol.* 2004;134:1683–96.
- Sharma M, Pande S. Unravelling effects of temperature and soil moisture stress response on development of dry root rot [*Rhizoctonia bataticola* (Taub.) butler] in chickpea. *Am J Plant Sci.* 2013;4:584–9.
- Sharma RC, Duveiller E, Ortiz-Ferrara G. Progress and challenge towards reducing wheat spot blotch threat in the Eastern Gangetic Plains of South Asia: is climate change already taking its toll? *Field Crop Res.* 2007;103:109–18.

- Smit AL, Vamerali T. The influence of potato cyst nematodes (*Globodera pallida*) and drought on rooting dynamics of potato (*Solanum tuberosum* L.). *Eur J Agron*. 1998;9(2–3):137–46.
- Smith AM, Stitt M (2007) Coordination of carbon supply and plant growth. *Plant Cell Environ*. 2007;30:1126–49.
- Suzuki N, Rivero RM, Shulaev V, Blumwald E, Mittler R. Abiotic and biotic stress combinations. *New Phytol*. 2014;203(1):32–43.
- Ton J, Flors V, Mauch-Mani B. The multifaceted role of ABA in disease resistance. *Trends Plant Sci*. 2009;14:10–317.
- Vile D, Pervert M, Belluau M, Vasseur F, Bresson J, Muller B, et al. *Arabidopsis* growth under prolonged high temperature and water deficit: independent or interactive effects? *Plant Cell Environ*. 2012;35:702–18.
- Wang Y, Bao Z, Zhu Y, Hua J. Analysis of temperature modulation of plant defense against biotrophic microbes. *Mol Plant Microbe Interact*. 2009;22:498–506.
- Whenham RJ, Fraser RSS, Brown LP, Payne JA. *Tobacco-mosaic virus*-induced increase in abscisic acid concentration in tobacco leaves: intracellular location in light and dark-green areas, and relationship to symptom development. *Planta*. 1986;168:592–8.
- Xu P, Chen F, Mannas JP, Feldman T, Sumner LW, Roossinck MJ. Virus infection improves drought tolerance. *New Phytol*. 2008;180:911–21.
- Yasuda M, Ishikawa A, Jikumaru Y, Seki M, Umezawa T, Asami T. Antagonistic interaction between systemic acquired resistance and the abscisic acid-mediated abiotic stress response in *Arabidopsis*. *Plant Cell*. 2008;20(6):1678–92.